INVESTIGATION OF INSULATING PROPERTIES OF LOW VACUUM IN EXTREMELY NON - UNIFORM FIELD CONFIGURATIONS BY AC POWER FREQUENCY VOLTAGE

By

MANISH KUMAR AGRAWAL

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

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CERTIFICATE

It is certified that the work contained in the thesis ntitled, "Investigation of Insulating Properties of low Vacuum in xtremely Non-Uniform Field Configurations by ac Power Frequency oltage", by Manish Kumar Agrawal has been carried out under my upervision and that this work has not been submitted elsewhere or a degree.

(Ravindra Arora)
Dept. of Electrical Engineering
Indian Institute of Technology
Kanpur 208 016

September, 1992

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ABSTRACT

Corona or stable partial discharge in gaseous dielectrics occur under extremely non-uniform field conditions. This leads to a deterioration in the insulating properties of gases.

In this thesis measurements have been made on the corona inception voltage and breakdown voltage of air in the low vacuum range of pressures upto 1 Torr under different electrode configurations. The electrode configurations are point – sphere (3 cm and 5 cm gaps), and small sphere – large sphere (3.7 cm ga). All the three configurations are expected to produce extremely non-uniform fields.

A pressure vessel has been used in this work to enclose the electrodes and to make measurements at different pressures. It had a transparent cover to allow visual inspection of glow and breakdown.

Measurements have also been made for the conduction currents. However, these were found to be measurable only under glow-discharge conditions around 1 Torr pressure.

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CHAPTER 1

INTRODUCTION

1.1 SCOPE OF THE WORK

In the present work, the investigation of insulation properties of air under low vacuum conditions in extremely non-uniform fields is being presented. Extremely non-uniform fields are present most often in electrical systems at edges and sharp points. These cause partial discharges which lead to a deterioration in the insulation properties of the dielectric. In this thesis, measurements have been made on the corona (or partial discharge) inception voltage as a function of pressure and gap distance between the electrodes in low vacuum.

Two different configurations have been used to obtain extremely non-uniform fields. One is a point and a plane, the other is a small sphere and a large sphere. These configurations are representative of typical real-life systems.

At lower pressures (1 Torr) a brilliant glow was observed in the entire gas chamber. Measurements of the conduction current between the electrodes under these conditions were performed. The conductivity of air under these conditions measured to be very high.

Earlier work in this field has been mostly on gaps upto 1 cm. For larger gap distances the breakdown strengths are extrapolated

from the known strengths of smaller gaps. This is quite dangerous as larger gaps have lower strengths than smaller gaps. Also, most work is in the high vacuum (10^{-6} - 10^{-9} Torr) range.

In this thesis measurements have been made on larger gaps (> 3 cm) in the low vacuum range (760 Torr - 1 Torr).

1.2 HISTORICAL DEVELOPMENT

High vacuum of the order of 10^{-4} - 10^{-6} Torr is finding a variety of applications in contactors, interrupters and capacitors because of its excellent combination of insulating and arc-quenching properties. These contactors are very popular for voltages upto 33 kV. /1/ These are being manufactured in our country by a few manufacturers also.

Considerable amount of work has been done to determine the electrical and especially arc-quenching properties of high vacuum with the main intention of using it for applications in power devices and apparatus. The greatest incentive for using vacuum to interrupt high currents is the rapid recovery of insulation strength in a vacuum gap. However, the present work is on the behaviour of two vacuum (upto 1 Torr) as insulation.

One of the most recent development is the vacuum being considered as a suitable insulation for high power electrical circuits aboard spacecrafts. The star wars programme in USA has led to the space power experiments abroad rockets (SPEAR) /2/. These were designed to establish the basis for developing and deploying pulsed power systems that make use of the space vacuum as an insulating medium. The main problem in the use of space vacuum as insulation is the presence of ambient plasma.

The atmosphere in the low earth orbit (about 300 kms. from the earth's surface) consists of charged particles, electrons and ions in addition to neutral molecules and atoms present in laboratory vacuum systems. This atmospheric condition is described by the term ambient plasma.

Insulation systems to be used in space have to be light weight. Of all the dielectrics used on the ground, only electronegative gases are light enough. But the containers needed to contain these gases are large and heavy. Hence the space research efforts to investigate the use of ambient plasma as an insulation in the low earth environment. This plasma is automatically replenished and does not deteriorate with breakdown.

.3 OUTLINE OF CHAPTERS

In Chapter 2 a brief description of the phenomena of electrical breakdown and partial discharge in gaseous dielectrics has been presented.

The entire set-up used to make measurements in the laboratory has been described in Chapter 3.

The results of measurements on corona inception voltage, breakdown voltage and conduction currents have been presented in Chapter 4.

Finally in Chapter 5, conclusions have been drawn from these results.

CHAPTER 2

ELECTRICAL BREAKDOWN OF GASES

.1 IONIZATION OF GASES

Air is an excellent insulator even at normal temperature and ressure. Whatever conductivity is possessed by air in this state esults from cosmic radiation and radiations from radio-active ubstances present on the earth and in the atmosphere. In the resence of high electric fields particles may gain sufficient nergy between collisions to cause ionization on impact with eutral molecules. During inelastic collisions with gas olecules, electrons lose a large fraction of their kinetic energy hich gets transformed to potential energy. This may cause onization of the struck molecule. Under high field strengths, onization by electron impact is the most important process eading to breakdown of gases. The energy gained by the electrons long the mean free path is a very important parameter that etermines the behaviour of ionization by electron impact. /3/

If $\bar{\lambda}_e$ is the mean free path in the field direction of trength E, then the average energy gained over the distance $\bar{\lambda}_e$ is $W = eE\bar{\lambda}_e$. From the kinetic theory of gases, we know that $\bar{\lambda}_e$ is nversely proportional to p. Hence ΔW is proportional to E/p. to ause ionization on impact, the energy ΔW must be at least equal o the ionization energy of the molecule. Also, electrons with

ɔwer energy may excite particles which on collision with other ɔw energy molecules may get ionized. Further, not all electrons ith energy greater than ionization energy will cause ionization y collision. Impact ionization involves the probability of ollision and for every gas there exists an optimum energy range n which ionization probability is maximum.

The fundamental processes that govern the breakdown of gases t high voltages are ionization and decay. Further, there are two ocations in gas insulated systems (GIS) where either or both hese processes may occur. These are the gas and the electrode urface. Before studying the mechanisms of breakdown, a summary f ionization and decay processes is given in the following.

.2 GAS PROCESSES

.2.1 Ionization Processes

Ionization takes place in the gas by the following processes:

1) Impact ionization

2) Photo ionization

3) Ionization by interaction of metastables with atoms

4) Thermal ionization

mpact Ionization

When the field increases, electrons gain enough energy etween collisions to cause ionization on collision with gas olecules. In terms of α, Townsend's first ionization oefficient, the current is

$$I = I_0 \, e^{\alpha d}.$$

The term $e^{\alpha d}$ is called the electron avalanche and it represents the number of electrons produced by one electron in travelling from cathode to anode. The ions produced during this process drift towards the cathode where they are collected.

Photo Ionization

Short wavelength photons can cause ionization of atoms upon collision. Photons are generally produced when an excited molecule returns to its ground state.

Photo ionization is essential in the streamer breakdown mechanism and some corona discharges.

Thermal Ionization

This is the term used to describe the ionizing actions of molecular collisions, radiation and electron collisions occurring in gases at high temperature. This is the principal source of ionization in gases and high pressure arcs at temperatures above 1000^{o}C.

Impact ionization and photo-ionization are the most significant ionization processes involved in our experiment.

2.2.2 De-Ionization Processes

Deionization takes place in the gas by the following processes:

1) Re-combination
2) Attachment - negative ion formation
3) Diffusion

Re-combination

At high pressures positively and negatively charged particles can recombine releasing their energies as a quantum of radiation.

Attachment

Electronegative gases like SF_6 attract electrons forming negative ions. This reduces the avalanche strength and is responsible for the high dielectric strength of SF_6.

Diffusion

Whenever there is non-uniform concentration of ions, there occurs a movement of ions from regions of high concentration to regions of low concentration. this has a de-ionizing effect in regions of high concentration.

Diffusion is particularly important in streamer discharge.

2.3 CATHODE PROCESSES

The cathode plays a very important role in discharge process by supplying electrons for initiating, sustaining and leading to breakdown of the dielectric. Under normal conditions electrons are bound to the cathode by electrostatic forces between the electrons and the nuclei.

2.3.1 Ionization processes

Ionization can take place at the cathode by the following processes:

1) Emission by positive ion impact
2) Photoelectric emission
3) Thermionic emission
4) Field emission

Positive ions or ultra-violet photons can release electrons on impact with the cathode. At temperatures above 2000 K the violent lattice vibrations give electrons sufficient energy to cross the surface barrier of the cathode surface. Very strong electric fields present near fine wires and sharp points under high vacuum can draw out electrons from the surface by the tunnel effect.

2.4 MECHANISMS OF BREAKDOWN

The basic mechanism of breakdown in gaseous dielectrics in uniform field was given by Townsend.

2.4.1 Townsend's Mechanism

The electrode current varies with voltage as: /3/

$$I = I_o \frac{e^{\alpha d}}{1 - \gamma\ (e^{\alpha d} - 1)}$$

where α, γ are Townsend's first and second ionization coefficients respectively and d is the electrode separation.

Using this relation, the breakdown voltage of the gap can be determined. We can also write that $V_b = F\ (p.d)$. This means that for a particular gas and electrode material the breakdown voltage is a unique function of the product of pressure and electrode separation. A plot of V_b versus the product p.d is called the Paschen's curve.

Townsend's mechanism is valid only for uniform electric fields when the electric field of the space charge produced by the electrons and ions can be neglected compared to the external field E_o in uniform field condition.

In our experiment since the field is non-uniform, Townsend's mechanism is not valid.

2.4.2 Streamer Mechanism

When the concentration of space charge in the avalanche increases to 10^8, the growth of the avalanche is strengthened. This occurs for large gap distances and high pressures. The electric field around an avalanche can be shown diagramatically as follows:

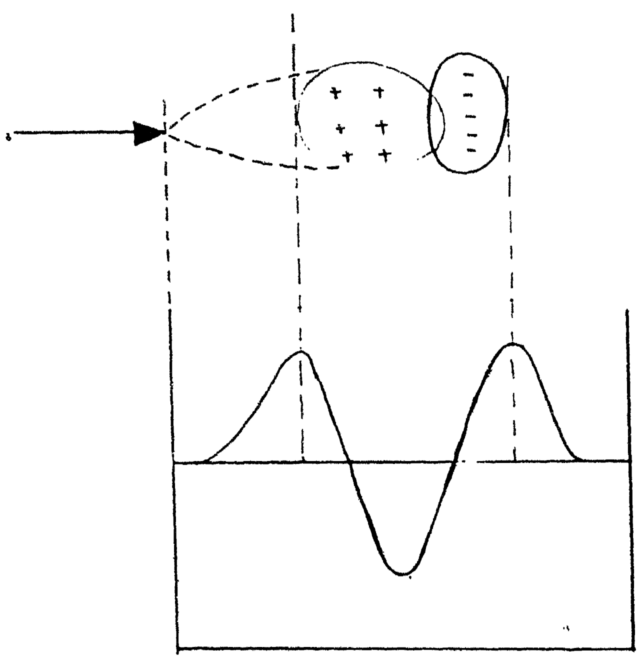

Fig. 2.1: Electric field around an avalanche.

The Laplace equation $\nabla.\bar{E} = q_{in}$ can be used to predict the effect of space charge on electric fields. For $n > 10^8$ the field distortion at the two ends of the avalanche and in the region between the electrons and ions becomes noticeable and becomes

comparable in magnitude to the applied external field. This leads to initiation of a streamer. Space charge fields play a very important role in the non-uniform field gaps giving rise to stable partial discharge before the breakdown.

At pressures comparable to atmosphere the discharge (breakdown) is observed to take much less time to form than explained by the Townsend Mechanism. Cloud chamber pictures show that under these conditions the strong space charge field leads to the formation of secondary avalanches which feed into the main avalanche. This leads to rapid development of breakdown channel.

Streamers are not likely to form in small gaps (of mm range) because if $d < x_c$, streamers cannot form. The condition for streamer are:

1) space charge concentration > 10^8
2) space charge field approaches the externally applied field.

Both these conditions follow from each other.

2.5 BREAKDOWN IN NON-UNIFORM FIELDS

In non-uniform fields, the effective ionization coefficient $\bar{\alpha}$ varies across the gap. the electron multiplication is then governed by the integral of $\bar{\alpha}$ over the path. The Townsend criterion takes the form

$$\gamma \left[\exp \left(\int_0^d \bar{\alpha} \, dx \right) - 1 \right] = 1$$

which is applicable to low pressure gases. The integration is done along the path of the highest field strength. If the gap

distance is less and the field is only slightly non-uniform, the above relation can be used for higher pressures too.

The condition for inception of discharge may be modified to make it applicable for the general case, taking into account the non-uniform distribution of $\bar{\alpha}$ as: /3/

$$\exp \int_{0}^{x_c < d} \bar{\alpha}\, dx = N_{cr}$$

where d is the gap length, N_{cr} is the critical electron concentration in an avalanche giving rise to initiation of streamer ($\approx 10^8$) and x_c is the path length of the avalanche to reach this size.

The strongly divergent field of a positive point plane is shown below:

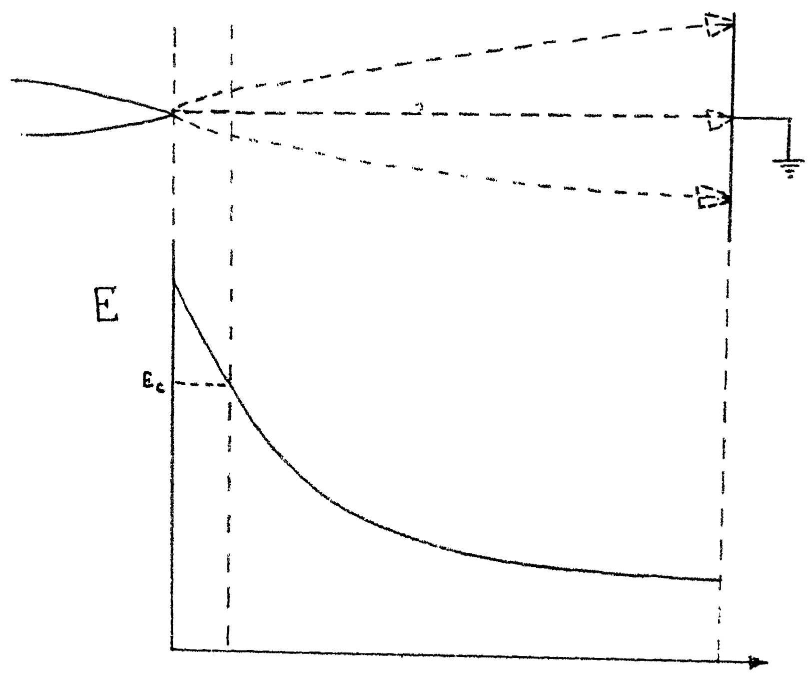

Fig. 2.2: Electric field in a point-plane gap.

2.5.1 Breakdown Strength in Extremely Non-Uniform fields

In extremely non-uniform fields, the breakdown strength of gaseous dielectrics depends upon the type of stable corona or PD that precedes the breakdown. The type of stable corona are:

1) Glow corona : occurs at extremely sharp points.
2) Streamer corona : occurs at relatively smoother electrodes in gap distances of cm range.
3) Leader corona : occurs at smooth electrodes at very large gap distances (in metres range).

2.6 PARTIAL DISCHARGES (PD)

Any electric discharge that does not completely bridge the electrodes is called a partial discharge. /5/ Although the magnitude of such a discharge is usually small, it causes progressive deterioration of the insulation. Hence the importance of the detection of partial discharge in a high voltage systems.

Partial discharges in gaseous dielectrics are known as corona. Corona discharges occur in gases at sharp points under extremely nonuniform electric fields. High field intensities at sharp points and edges cause a partial breakdown of the surrounding air.

In uniform and weakly non-uniform fields, inception of PD leads to immediate breakdown. In extremely non-uniform fields, long before total breakdown, stable PD are observed. These are called Coronas. In HV transmission and distribution these become very important as extremely non-uniform fields are unavoidable.

Ionization produces space charge. The fields produced by these space charges lead to a distortion in the voltage profile

between the electrodes. A partial discharge removes the space charge and leads to an equalization of the potential.

2.7 DISCHARGE BY AC VOLTAGE

Our experiments were conducted under ac voltage and this was the type of corona observed. Hence it is described here in some detail.

For the study of internal discharges, dielectrics are modelled by the a-b-c circuit shown below: /5/

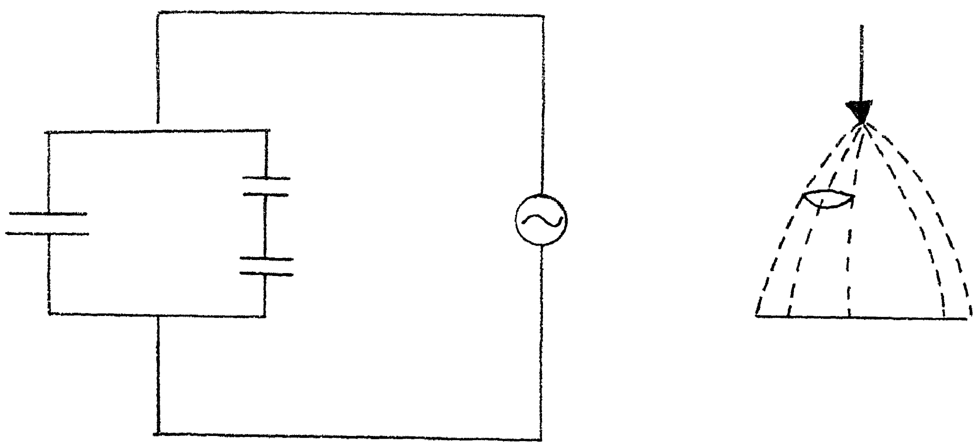

Fig. 2.3: Modelling of ac corona.

The sound part of the dielectric is represented by capacitance a, the cavity by capacitance c and the dielectric in series with the cavity by capacitance b. When ac voltage is applied, c is capacitively charged, breaks down when it reaches break down voltage, charges again, breaks down. This process continues.

When v_c, the voltage across the cavity reaches break down voltage U^+, a discharge occurs in the cavity, which reduces its voltage to V^+ (usually less than 100 V). This extinguishes the discharge. After the discharge has been extinguished, the voltage over the cavity increases again. Since the voltage drop occurs very fast, it is observed almost as a pulse.

This pulse must be distinguished from the Trichel pulse of negative corona which occurs only under dc voltage.

The voltage in the cavity is the result of the superposition of the applied voltage and the field produced by the surface charges left at the cavity walls after the last discharge. A little analysis shows that these fields counteract each other. When the applied voltage begins to decrease, the cavity voltage too falls to U^- and a new discharge occurs. In this way, groups of regularly recurrent discharges are found.

The discharges in the cavity cause current impulses in the leads of the sample given by $i = c \frac{dV}{dt}$. These impulses are concentrated in regions where the voltage applied to the sample increases or decreases most which, for a sinusoidal voltage is at the zero points. When the two half-cycles are of the same voltage, the impulses when observed on an oscilloscope give a stationary picture of 50 Hz recurrence frequency.

The ac voltage across the sample at which discharges begin to occur when the voltage is increased is called the inception voltage. If the voltage is decreased after discharges have started, the voltage at which discharges extinguish is lower than the inception voltage and is called the extinction voltage.

The persistence of the discharge after the voltage has been lowered can be explained using the field generated by the residual surface charges which are left by the previous discharge. In the alternate half-cycle the applied voltage and the field of the surface charge aid each other and theoretically the discharge can persist even when the applied voltage is half the inception voltage. In practice however, the extinction voltage is about 20 - 30% lower than inception voltage.

If the a.c. voltage is slowly increased, corona discharges first occur at the negative half cycle only. At first one discharge peak per cycle is observed. When the voltage is increased fractionally, the number of impulses grows rapidly. the pulses are equal in size and increase in number almost linearly with voltage.

When the voltage is increased impulses also appear at the positive half-cycle. These are slightly larger in size.

2.8 MAGNITUDE OF PARTIAL DISCHARGE

We need to determine the harmfulness of the discharges. To do this we need a physical quantity that is related to the harmfulness of the discharge and can be measured by some standard methods. One physical quantity that satisfies both the above requirements is q, the charge displaced in the leads of the sample. /5/ q is called the apparent charge. The various favourable features in using q are:

1) q is directly related to the energy dissipated in the discharge.

2) q is directly related to the size (volume) of the defect in insulation.

3) q can be readily measured by an electric discharge detector.

We have therefore used q, the apparent charge, as the quantity that determined the magnitude of discharge. The only disadvantage in using q as a measure for discharges is that q is inversely proportional to the insulation thickness d. Hence thick insulations are measured with less sensitivity than thin ones.

2.9 NON-ELECTRICAL DETECTION OF PARTIAL DISCHARGE

Discharge can be measured in two ways:

1) Non-electrically

2) Electrically

Non-electrical methods can be used to detect the presence of discharges when the discharge magnitude is not required to be measured. Two of the most important phenomena used are sound and light.

2.9.1 Sound

Detection of discharge by ear is a very standard and established practice. Discharge of a few hundred pico-coulombs can be heard. In very quiet environments even 50 pc of discharge can be heard. However, even a small amount of background noise will spoil this sensitivity.

2.9.2 Light

After being in the dark for about 15 minutes, the human eye becomes very sensitive to light. Still, the smallest possible discharge that can be detected by light is about 500 - 1000 pc.

The non-electrical methods were not useful in our measurements as we desired a higher sensitivity which could only be obtained using electrical detection techniques.

2.10 ELECTRICAL DETECTION OF PARTIAL DISCHARGE

The detection of current impulses in the leads of the sample forms the basis of this method of detection.

2.10.1 Detection Circuits

The basic diagram of the circuit used to detect partial discharge currents is shown below:

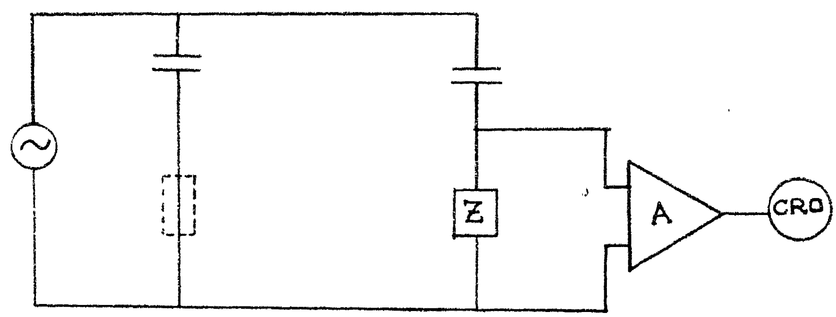

Fig. 2.4: PD Detection Circuit.

1) A high voltage source, preferably discharge free.
2) Sample a, affected by discharges.
3) Impedance z, across which current impulses produce voltage impulses.
4) Coupling capacitor C, which facilitates passage of high frequency impulses.
5) Amplifier A.
6) Oscilloscope O.

The impedance Z can be connected to the sample in two different ways: (1) In series with the sample as in the figure, (2) In series with the capacitor, as represented by dotted lines. Both connections are electrically the same, but in practice, the connection of z is important. If the sample is large, as in our experiments, the second configuration is used so that the large breakdown current does not pass through the impedance z. The impedance normally used are parallel combination of R-C or an oscillatory LCR circuit. On analysing the response of both these circuits the following statements can be made:

1) The height of the voltage impulse is proportional to the magnitude q of the discharges. This way, the magnitude of the discharge can be measured.

2) The height of the impulse is independent of R. However, if R is small, the time constant is small and the pulses are very sharp. These sharp pulses may not be amplified fully in some amplifiers. Hence, it is useful to have a variable impedance that can be matched to the sample capacity.

3) In the absence of the coupling capacitor C, the impulses become very small. Hence the coupling capacitor is essential.

The circuit generates a characteristics signal - a series of short impulses which appear in clusters with a repetition frequency of 50 Hz.

The sensitivity of the discharge detection circuit is defined by the smallest partial discharge that can be observed in the presence of noise. The magnitude of this smallest detectable discharge is expressed in pico-Coulombs.

2.10.2 Noise

The two sources of noise in the detection circuit are: (1) The amplifier, (2) The circuit.

The effects of the above two sources of noise may be studied and results obtained. However, in practice this sensitivity is not obtained. Electromagnetic interference, disturbances in the mains and earth leads, extraneous noises generally determine the sensitivity.

2.10.3 Display

The best way to observe the impulses of partial discharges is to display them on an oscilloscope. The discharge impulses can be displayed at a time base of the same frequency as the applied test voltage. A stationary picture is produced. To relate the timing of the impulses to the phase angle of the test voltage, the impulses can be super imposed on the sine wave of the test voltage.

2.10.4 Sensitivity of Detection

The sensitivity of detection of a detector circuit is the smallest magnitude of discharge that it can detect. Using calibrators we can get a pre-determined quantity of charge in the detection circuit. This gives us an estimate of the sensitivity of the detection circuit.

Calibrators

Discharges of constant magnitude can be made electronically or physically. Physical placement of discharge may require a

source of corona. Electronic means use the principle of division of charge by two capacitors in series.

There are two kinds of electronic calibrators:

1) Square wave generator.

2) Portable calibrator.

The square wave generator generates a square wave of voltage which injects a charge in the capacitance in series with the generator. This impulse causes a voltage impulse in the detection circuit.

Portable Calibrator

The portable calibrator works on the same principles as the square wave generator. Some of its features are:

1) It is small and can be taken into the H.V bay to be connected over the sample.
2) It is battery driven.
3) It's internal capacitance is a few p.F.
4) It produces one or two impulses per cycle.
5) It incorporates a photocell that detects the ambient lighting of the laboratory. Thus the calibrator can be synchronized with the test voltage.
6) It provides a fixed set of discharge magnitudes – 5,50,100,250 pc.

The sensitivity of detection in the laboratory set up was 25 pC. This discharge produced voltage pulses of 50 mV which were observed on the oscilloscope. Discharges of smaller magnitude could not be reliably distinguished from background noise.

2.10.5 Interference

Interference seriously affects the sensitivity and reliability of detection circuits. Maximum sensitivity cannot be attained if the noise generated by foreign signals is larger than the thermal noise of the circuit. When the test voltage is raised, foreign signals often appear which can be mistaken for discharge signals from the sample.

The main causes of interference are (1) Mains (2) High voltage circuit, (3) Pick-up, (4) Contact noise.

In areas where electronic switching occurs, filtering becomes essential to suppress harmonics.

If the high voltage leads are not designed properly, corona discharges occur at sharp points. Hence HV leads should be constructed from cylinders of sufficiently large diameter.

The circuit can pick-up electromagnetic radiation. The extensive loops formed by HV connections act as antennas which pick-up interference. Outside interference can be studied using metal cages called Faraday cages.

Badly earthed components or small floating parts also cause stable discharges. The test voltage induces small voltages in these contacts which are discharged periodically through faulty contacts. Metal bits or wires lying on the laboratory floor, corroded connections etc. produce induced discharges.

Multiple earthing creates common paths between the signal and disturbances. Hence there should only be a single earth contact.

Bad contacts or earthing cause disturbing signals and these tend to concentrate around the zero points of the sine wave and

are difficult to distinguish from discharge impulses. Hence for reliable results, the contacts should be proper and the earthing good.

2.11 MECHANISM OF DETERIORATION OF AIR

Discharges can cause deterioration of dielectrics by any of the following means:

1) Heating the dielectric boundary.
2) Charges trapped in the surface.
3) Attack by ultraviolet rays and soft x-rays.
4) Formation of chemicals such as ozone and nitric acid.

Corona discharges occurring around base conductors cannot attack insulation in the same way as internal and surface discharges. Indirect action by ozone formed by corona can deteriorate neighbouring dielectrics.

Harmful discharges must be distinguished from unharmful ones with the aid of discharge patterns. For instance, corona in air is not dangerous unless ozone and nitrides are able to injure the insulation. However, corona in sulphur hexaflouride is very detrimental. Therefore some hundreds of pico Coulombs of discharge may be permissible for corona in air, where a discharge of some pico coulombs may not be permissible in sulphur hexaflouride insulation. Permissible magnitude of discharges are found after extensive experiments.

In case of uniform and weakly non-uniform fields, no stable pd take place before the breakdown. Whereas in the case of extremely non-uniform fields stable pd always precede the breakdown.

Measurements in this work have been made for extremely non-uniform field configurations of the electrode set-up.

CHAPTER 3

EXPERIMENTAL SET-UP

Two different types of measurements under extremely non-uniform field conditions have been made in this work. These are:

1) Corona inception and breakdown voltages.

2) Conduction currents.

The set-up for each of these measurements are described below.

3.1 PARTIAL DISCHARGE MEASUREMENT SET-UP

The circuit used to measure corona inception and breakdown voltages is shown in Fig. 3.1.

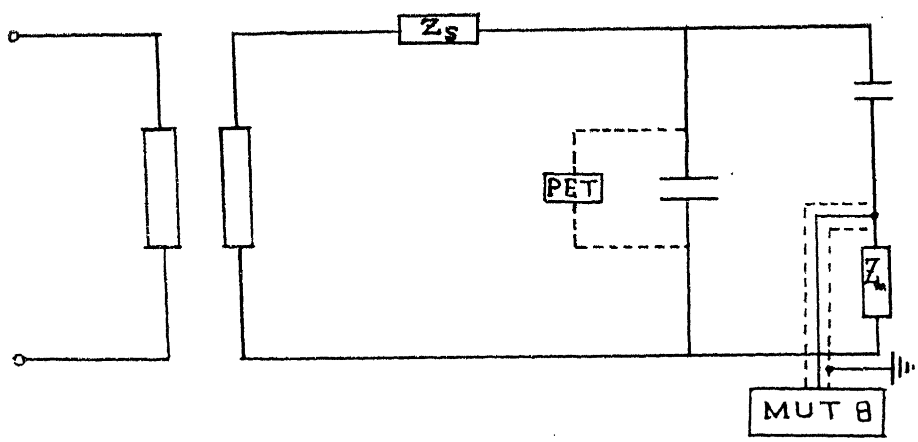

Fig. 3.1: Circuit diagram of partial discharge measuring circuit.

HVTr : High voltage transformer that is totally PD free

Z_s : Series impedance of the source.

P : test object i.e. pressure vessel.

C_c : Coupling capacitor, totally P.D. free upto 95 kV.

Z_m : Measuring impedance.

MUT8 : Partial discharge detector.

PET1 : Portable discharge calibrator.

3.1.1 PD Free Transformer

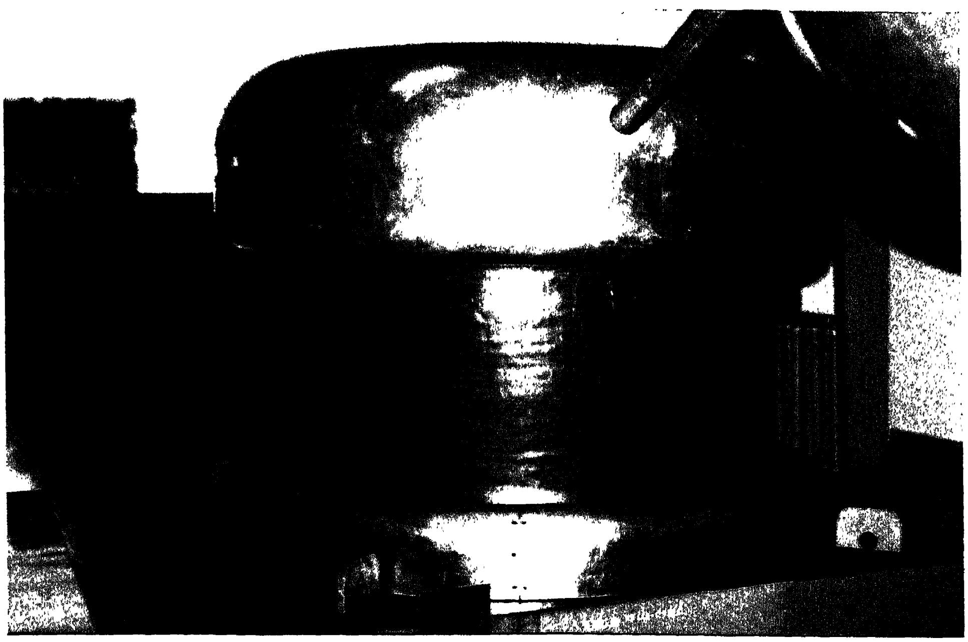

Fig. 3.2: PD Free test Transformer.

The H.V. test transformer has been made totally PD free till 95 kV by making secure electrical contacts at all points. The transformer is housed in a metal dome that prevents any PD at the HV point. The lead from the transformer is a well shaped metal pipe. There are no sharp edges that may cause PD.

The HV transformer is single phase and has ONAN (oil natural air natural) cooling.

3.1.2 Pressure Vessel

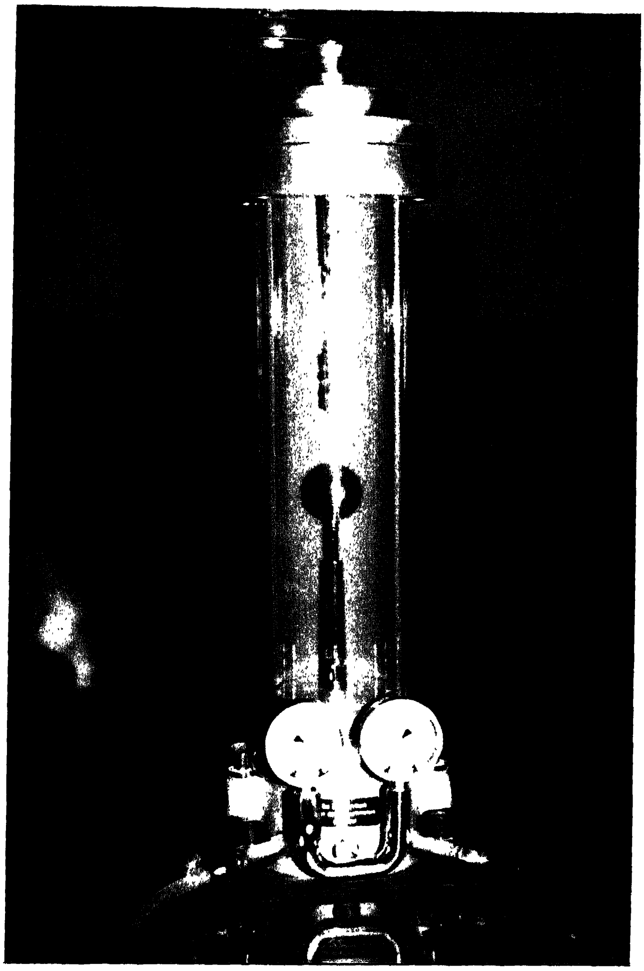

Fig. 3.3: Pressure Vessel.

This pressure vessel whose specifications are given below was used to house the electrodes under variable pressure. Maintaining a constant gap distance, pressure was reduced by running the pump. When the desired pressure was obtained, the input stop cock was closed. Now corona inception and breakdown voltages were measured

for the particular pressure and gap distance. To raise the pressure, the output stop cock could be opened till the pressure reached the desired level. This way all pressures from 760 Torr 1 Torr were obtained.

To make measurements for different gap distances the vessel was taken to a clean room (The IC Laboratory) where it was opened very carefully. With gloved hands to ensure that no dust or grease settled on the electrodes, the electrodes were unscrewed and set to different gap distance or were replaced by another set of electrodes. After making the desired setting, the vessel was closed again in the clean room, applying vacuum grease at the sealing rings. The design of the pressure vessel casing electrodes was such that sharp points were avoided to prevent P.D.

To ensure that no partial discharge occurred at the contact points to the vessel, the screws used to hold the high voltage flexible conductor were smooth edged.

Specifications of pressure vessel

Type	:	DKU
AC Voltage	:	100 kV (rms)
Impulse voltage	:	140 kV
Operating pressure	:	0 - 6 bar (0 - 4500 Torr)
Weight	:	12 kg
Height	:	70 cm
Diameter	:	15 cm

3.1.3 Voltage

The experiments have been conducted under ac voltage. Variable ac voltage was obtained by the 100 kV test transformer

which was supplied energy by a 0 – 240 V auto transformer.

The voltage was measured from the primary side. By suitable calibration the voltmeters directly recorded the high voltage output.

3.1.4 Electrode Set-up for Investigation

As mentioned earlier in Sec. 1.1, two electrode configurations were used to make measurements. One was the point – sphere configuration and the other was the small sphere – large sphere configuration. The specifications of the electrodes used are given below:

Point – sphere

Point electrode : tipradius = 0.02 mm

Sphere electrode: ϕ 50 mm

Small sphere – large sphere

Small sphere : ϕ 20 mm

Large sphere : ϕ 50 mm

The breakdown voltage of the gap is lowered when the electrodes are exposed to the atmosphere. Therefore, before breakdown voltages are recorded, the electrodes must be conditioned using any suitable method, so that the observations are reproducible. Repeated breakdown (upto 1000 times) is one method of conditioning. However, this was not done in the experiment.

Another effective technique of conditioning is to clean the electrode surfaces with methanol. This is called chemical conditioning. During the experiment, each time the vessel was opened, the electrodes were cleaned with Methanol and the first

few breakdowns were not recorded to ensure that the recorded voltages were reliable.

3.1.5 Estimation of the Degree of Uniformity of the Field η

Electric fields are classified as follows:

a) Uniform fields

b) Weakly non-uniform fields

c) Extremely non-uniform fields

The degree of uniformity of a field is defined on the basis of the numerical value of the factor η, which is described by Schwaiger as following:

$$\eta = \frac{\bar{E}}{|E_{max}|}$$

where,

$\bar{E}$ = Average value of the electric field in the gap.

= V/d

V = voltage on the electrodes

d = electrode separation

$|E_{max}|$ = Peak value of the electric field in the gap (Calculated geometrically).

For uniform electric fields $\eta = 1$.

For weakly non-uniform fields, η may be around 0.2 for atmospheric air depending upon air and the electrode conditions. Any value less than this gives rise to an extremely nonuniform field.

The following table gives the values of η for each of the configurations studied.

Table 3.1: Values of η for different electrode configurations studied.

Configuration	Gap distance	η
Point - sphere	3 cm	0.03
Point - sphere	5 cm	0.02
Small sphere - large sphere	3.7 cm	0.3

η depends only upon the geometry of the electrode configuration. For the electrode setup used in the laboratory, the value of η was obtained from detailed curves of η vs. geometrical parameters (electrode separation and tip radius). /9/

3.1.6 Specifications of Detector Circuit Equipment

The partial discharge was measured electrically using the same configuration as explained earlier in the chapter on PD detection. The impedance z was connected in series with the coupling capacitor C_c to prevent large inrushing currents from damaging the impedance during breakdown.

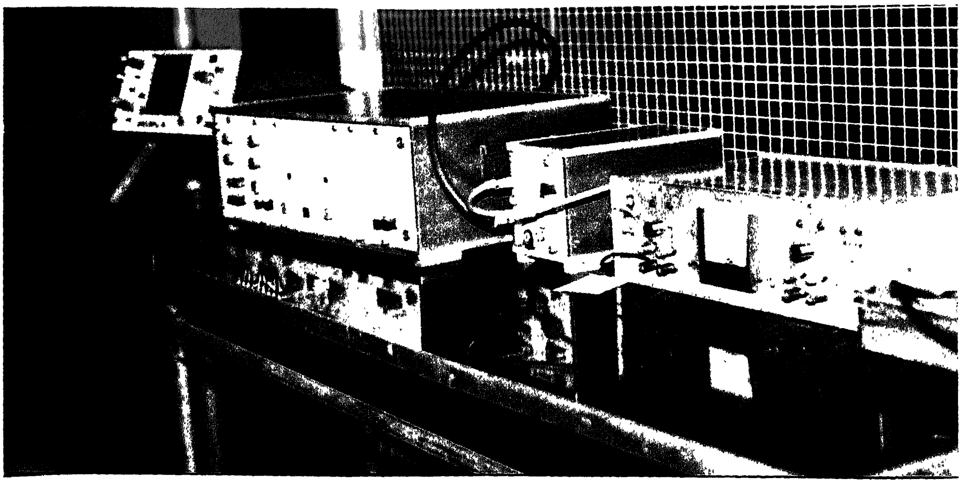

Fig. 3.4: Detector circuit.

Specifications are given below:

Coupling capacitor	:	Parallel Plate 1100 pF, 100 kV
Measuring impedance	:	Active impedance H 18, input resistance adjustable in 4 steps – 150 Ω / 680 Ω / 2.7 kΩ/ 12 KΩ.
Detector	:	MUT8, 1pC – 1000 pC measuring range with detection limit of 0.05 pC, anti-interference protection, oscilloscope required as an accessory.
Calibrator	:	PET2, 5, 25, 50, 250 pC pulse output, 100 Hz repetition frequency, light synchronized, 50 nS pulse rise time.
Vacuum Pump	:	Mechanical (rotary)
Gauge	:	Thermionic gauge, 1 torr – 10^{-2} torr scale.

3.1.7 Measurement of Pressure

It was not possible to use a single gauge to measure pressure from 760 torr to 1 Torr. Hence two different pressure gauges were used to record pressure. These were the mechanical gauge and the thermocouple gauge.

The diaphragm (mechanical) gauge measures pressure by the deflection of a diaphragm. This deflection is then amplified mechanically and transmitted to a rotating pointer. The pointer

indicates the pressure on a circular scale. This gauge was used to measure pressure from 760 Torr - 37 Torr.

The thermocouple gauge was used to measure pressure in the region of 1 Torr. The thermocouple gauge operates on the principle of equilibrium between heat supplied to a filament and heat lost by conduction to the surrounding gas. In the pressure range 1 torr - 10^{-4} torr, this conductivity is a direct function of the pressure of the gas.

3.2 CONDUCTION CURRENT MEASUREMENT SET-UP

The experimental set-up used to measure conduction currents is shown below:

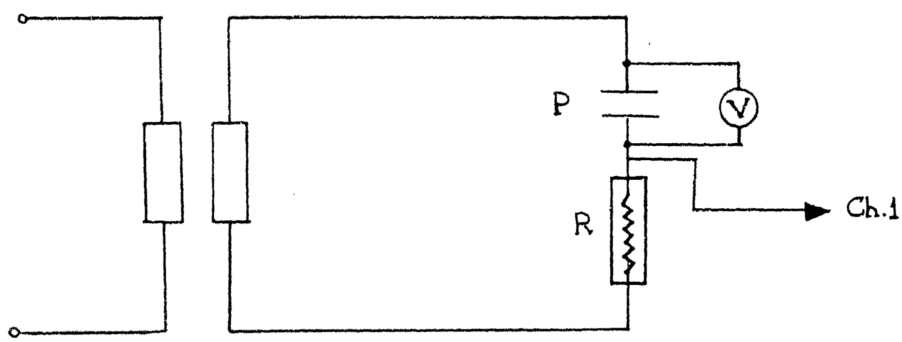

Fig. 3.5: Set-up to measure conduction currents.

The various elements are

X^r	:	0 - 5 kV Av. to transformer
P	:	Pressure vessel
V	:	ac voltmeter
R	:	Standard Resistance
Ch 1	:	Input to oscilloscope

Voltage was applied to the electrodes using an auto transformer. The voltage across the electrodes was measured by the ac voltmeter connected across the pressure vessel. The

standard resistance in series with the electrodes was used to record the conduction current. With this arrangement, the minimum peak current that could be measured was 0.2 μA. The current waveform was observed on the oscilloscope.

3.3 PRODUCTION OF LOW VACUUM

Our experiments have been performed under low vacuum conditions. This pressure was generated using a mechanical rotary pump.

The lowest pressure possible using a rotary pump is determined by the fact that at the exhaust port the gas is compressed into a small but definite volume. When the chamber pressure becomes so low that at maximum compression in the exhaust port the gas pressure is still less than atmospheric pressure, the compressed gas is not able to be ejected. Further, pumping action only re-expands and compresses the same gas without decreasing the pressure in the chamber. The lowest (ultimate) pressure achievable by a rotary pump is about 10^{-2} Torr.

In our set-up however, the lowest pressure achieved was 1 Torr.

3.3.1 Precautions in the use of Vacuum Chamber

) Cleaning

In vacuum systems cleaning is regarded not only as the emoval of visible dirt from the surfaces but also includes the ubsequent removal of all the contaminants like oil, grease or hose resulting from chemical reaction like oxides etc. physically tuck on the surfaces.

Oxides and other surface layers were removed by rubbing with the aid of detergents.

Oils and greases were removed by cleaning the electrodes with organic solvents. Methanol and TCE (Tetra chloro ethylene) were the solvents used. Distilled water was used for all cleaning operations as tap water could leave salts on the surface.

2) While opening the stop cock, tissue paper was placed over the nozzle to prevent dust particles entering the vacuum chamber.

3.3.2 Precautions in the use of Vacuum Pump

1) The level of oil in the pump was checked and maintained between the levels marked.

2) The pump was not run continuously for long periods as there was the danger of damage to the motor.

3) The presence of vacuum in the pump could cause oil to be sucked into the stator. Hence the pump (i.e. chamber) was vented to atmospheric pressure when power was turned off.

CHAPTER 4

MEASUREMENT RESULTS

The insulating properties of air and low vacuum in the range of 760 Torr to 1 Torr were investigated for two extremely non-uniform field configurations with the help of a pressure vessel.

The two electrode configurations investigated were the following:

1) A point and a sphere
2) A small sphere and a large sphere.

Investigations made to study the insulating properties of low vacuum can be characterised under the following two categories:

1) Measurement of corona inception (V_i) and breakdown voltages (V_b) in the gap.
2) Measurement of conduction currents

4.1 MEASUREMENT OF V_i AND V_b

Results of measurements on V_i and V_b are presented in this section.

4.1.1 Point-Sphere Gap

(a) 5 cm Gap

Table 4.1: Corona inception and breakdown voltages for point-sphere electrode configuration at a constant gap spacing of 5 cm.

P (Torr)	V_i (kV) (rms)	V_b (kV) (rms)
684	16	31
608	14.5	29
532	12.5	27
456	16	26
380	16	24
304	15.5	22
228	–	19
152	–	15
76	–	12

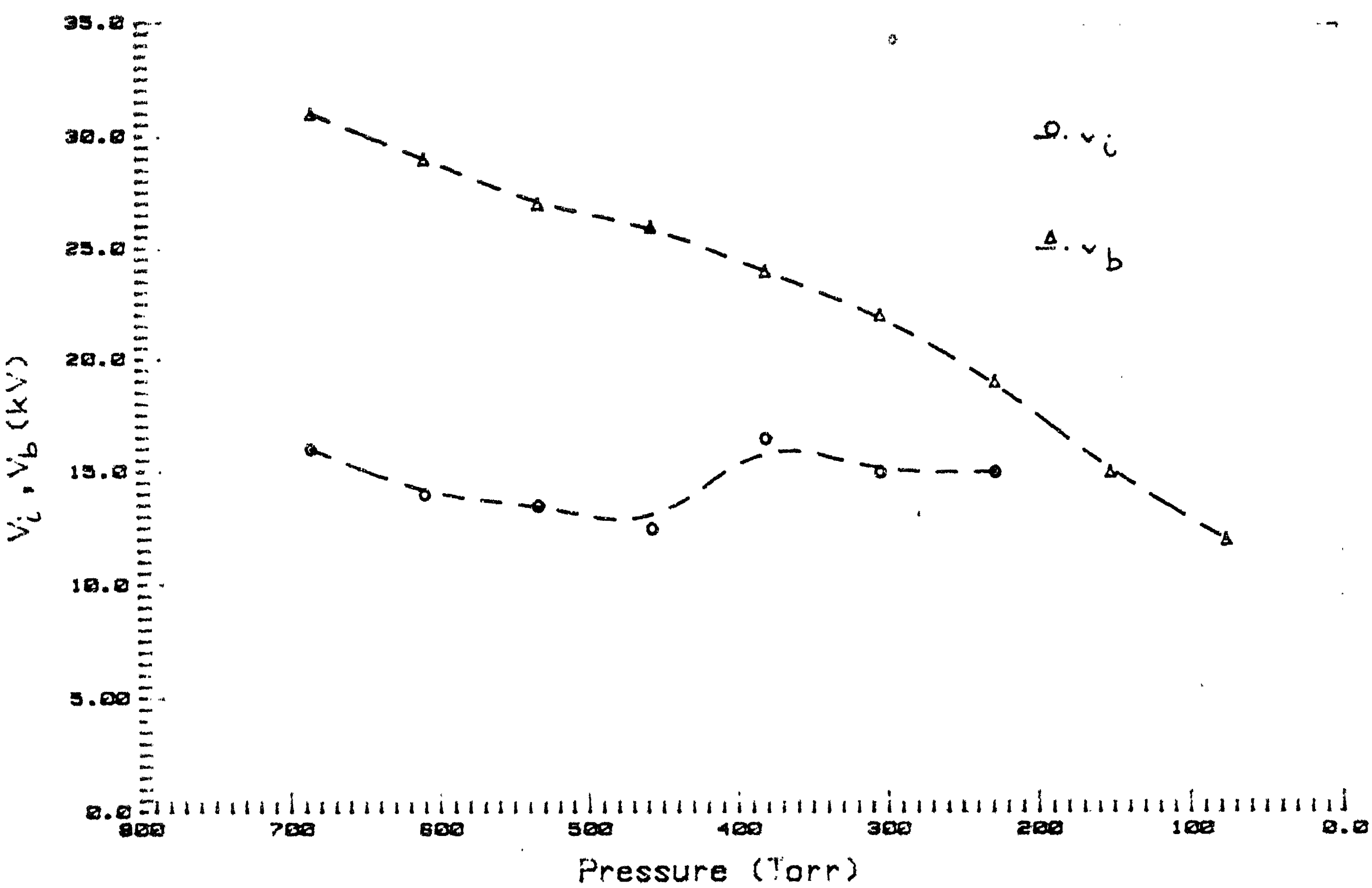

Fig. 4.1: Graphical representation of Table 4.1.

(b) 3 cm gap:

Table 4.2: Corona inception and breakdown voltages for voltages for point-sphere electrode configuration at a constant gap spacing of 3 cm.

P (Torr)	V_i (kV) (rms)	V_b (kV) (rms)
684	15.5	21
608	15.5	20
532	15	18.5
456	16	18
380	15.8	16
304	–	14.5
228	–	13
152	–	8.5
76	–	7.5

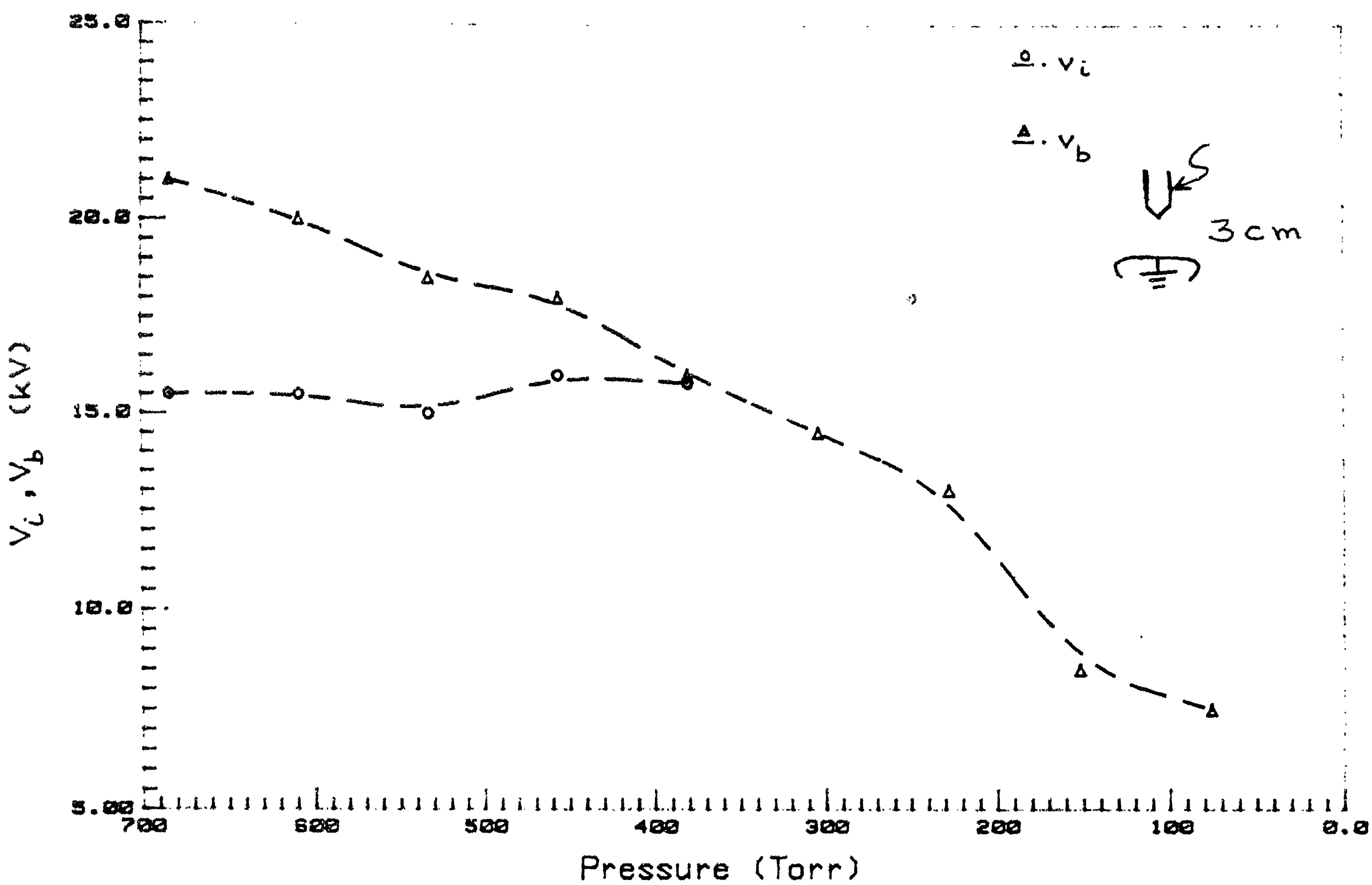

Fig. 4.2: Graphical representation of Table 4.2.

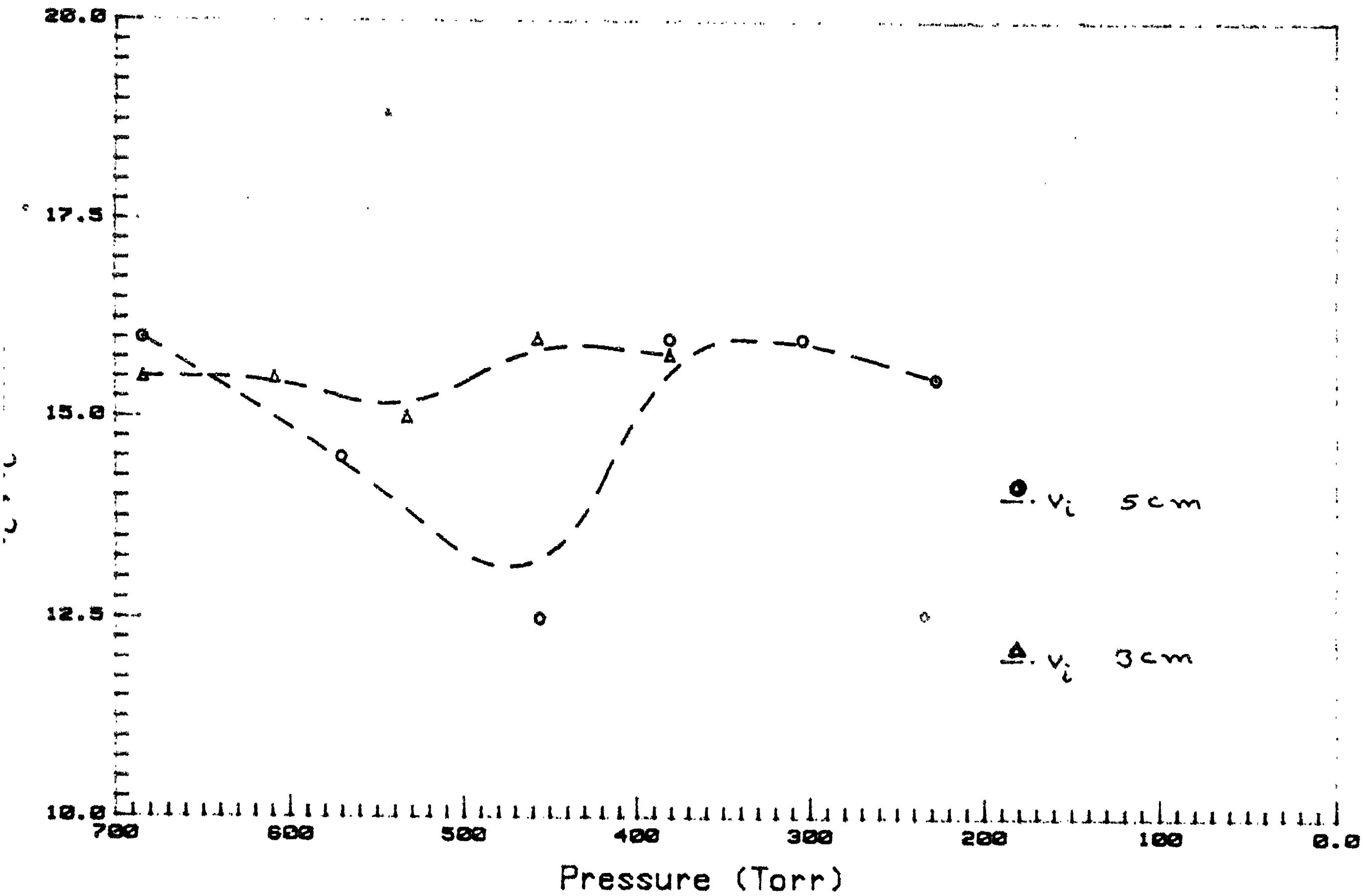

Fig. 4.3: Plot of corona inception voltage versus pressure for point-plane electrode configuration.

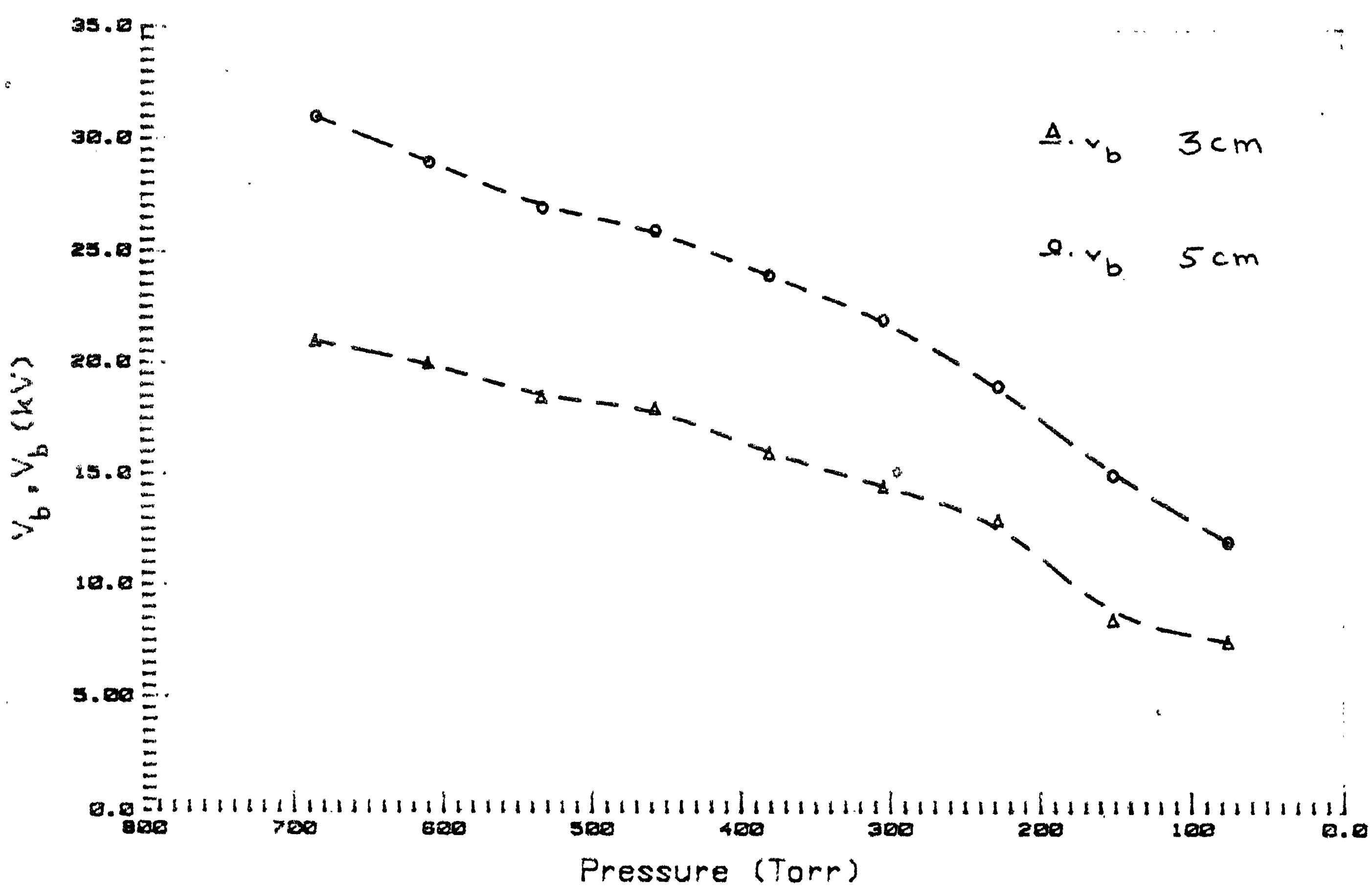

Fig. 4.4: Plot of breakdown voltage vs pressure for point-sphere electrode configuration.

4.1.2 Small Sphere - Large Sphere Gap

Table 6.3: Corona inception and breakdown voltage for a small sphere - large sphere gap at constant spacing of 37 mm.

P (Torr)	V_i (kV) (rms)	V_b (kV) (rms)
684	–	37.5
608	–	35.5
532	–	32
456	–	28
380	–	25.5
304	–	21
228	–	19
152	–	15.5
76	–	10.5

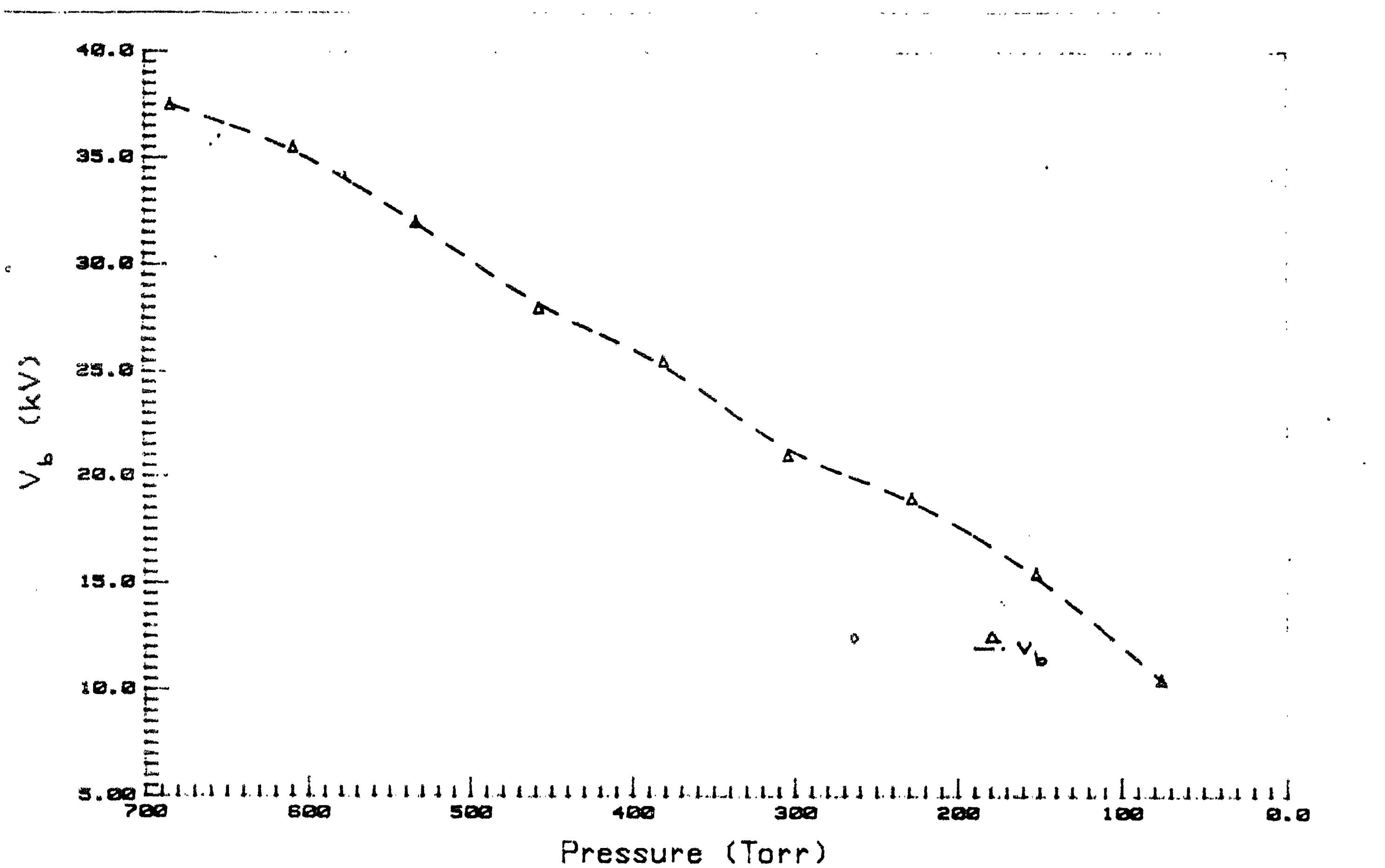

Fig. 4.5: Graphical representation of Table 4.3.

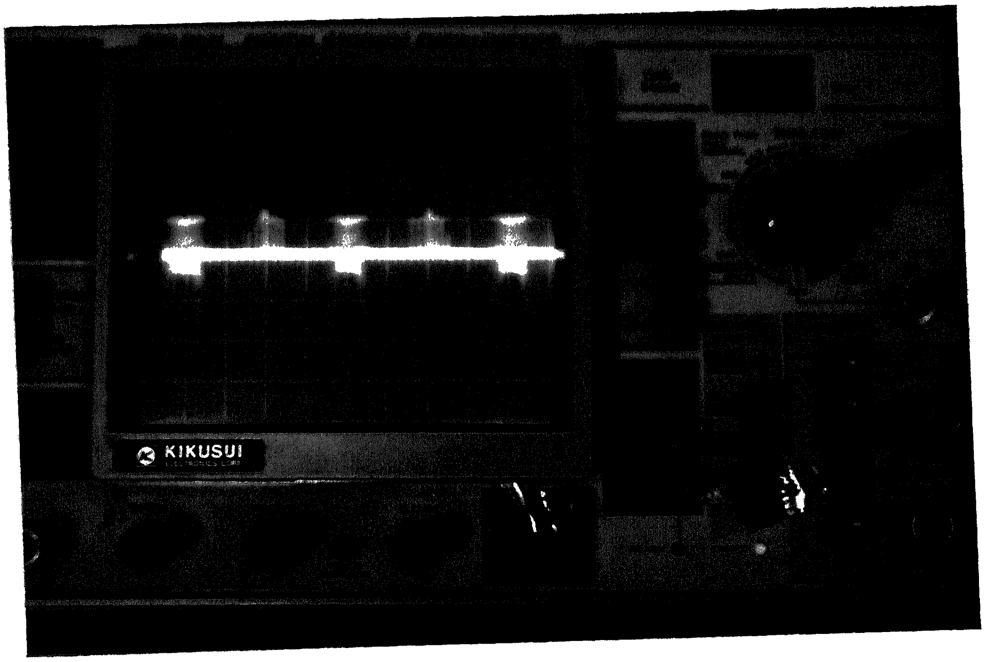

Fig. 4.6: Photograph of PD pulses on oscilloscope screen.

4.2 CONDUCTION CURRENT CHARACTERISTICS OF LOW VACUUM UNDER GLOW DISCHARGE CONDITIONS AT CONSTANT PRESSURE (1 TORR)

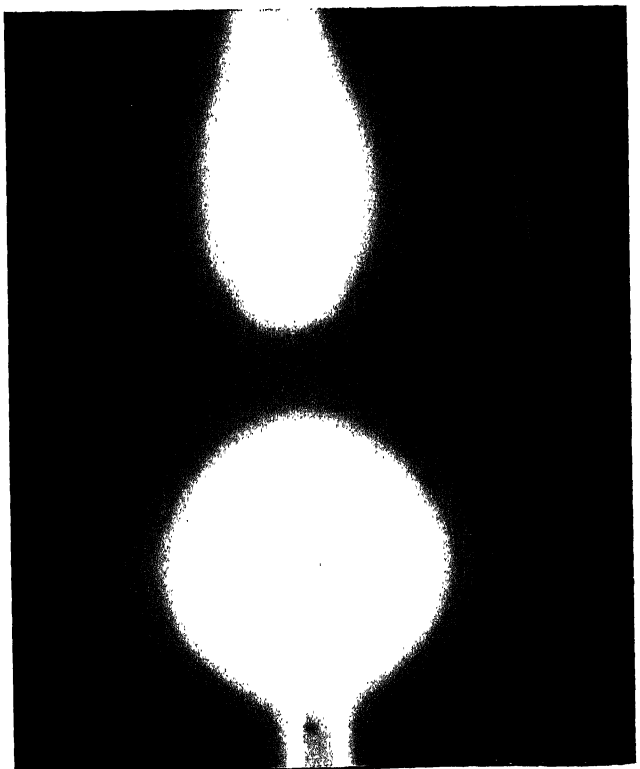

Fig. 4.7: Glow Discharge.

4.2.1 Point-Sphere Electrodes

(a) 5 cm gap

$V_i = 400$ V

$V_b = 525$ V

Table 4.4: Peak values of conduction current under glow discharge conditions for point-sphere electrode at a constant gap spacing of 5 cm.

V (Volts)	i_p^- (mA)	i^+ (mA)
400	1.8	–
410	9.2	–
420	11	–
430	16	16
440	19	19
450	20	22
460	22	26
470	25	30
480	28	34
490	34	38
500	38	42
510	46	50
520	60	68

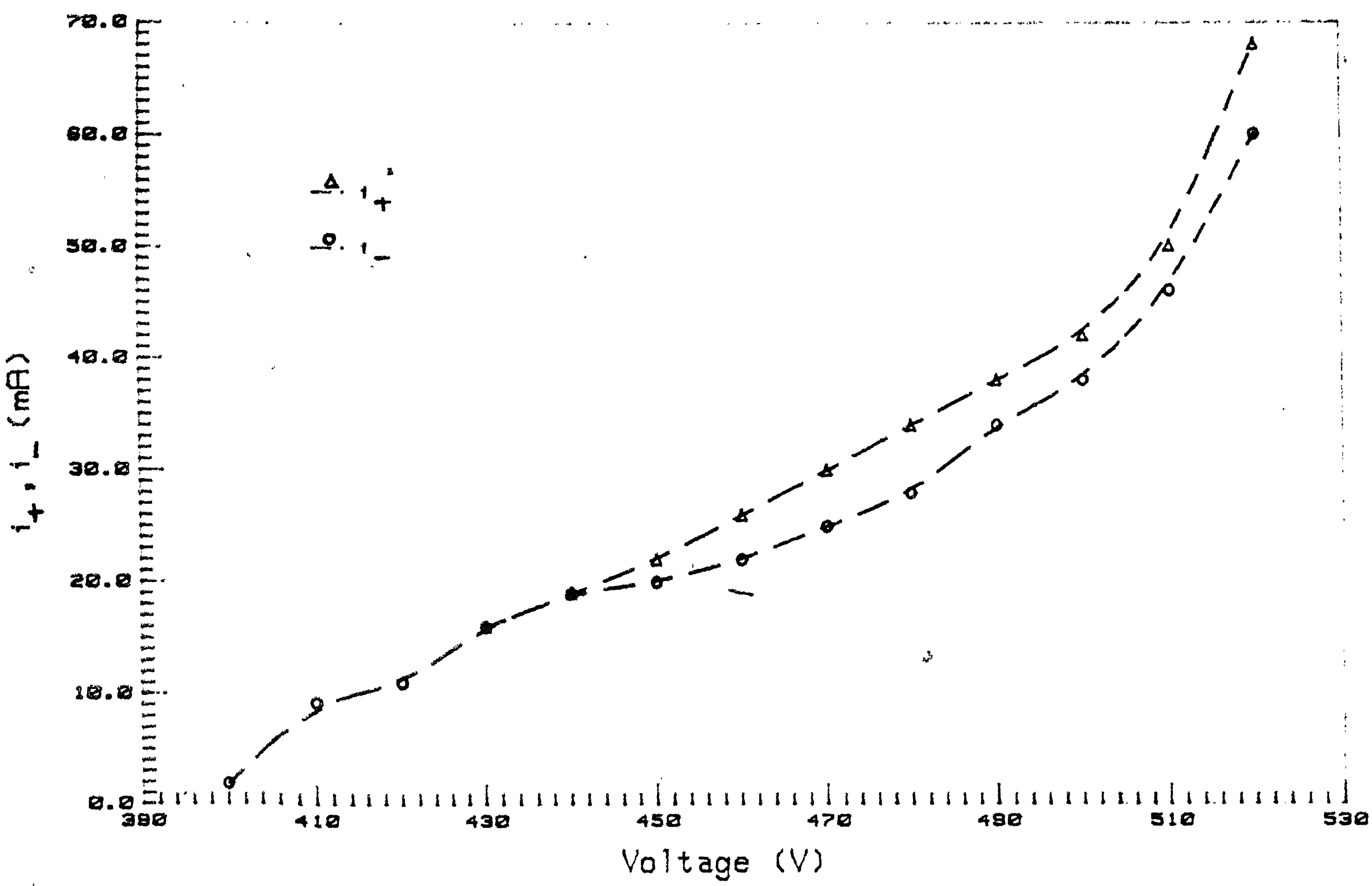

Fig. 4.8: Graphical representation of Table 4.4.

(b) 3 cm gap

V_i = 385 V

V_b = 525 V

Table 4.5: Peak values of conduction current under glow discharge conditions for point-sphere electrode at a constant gap spacing of 3 cm.

V (Volts)	i^- (mA)	i^+ (mA)
395	5	-
400	6	-
410	6.5	-
420	7	-
440	22	25
450	26	30
460	30	34
470	32	37
480	38	42
490	52	56
500	68	72
510	76	80

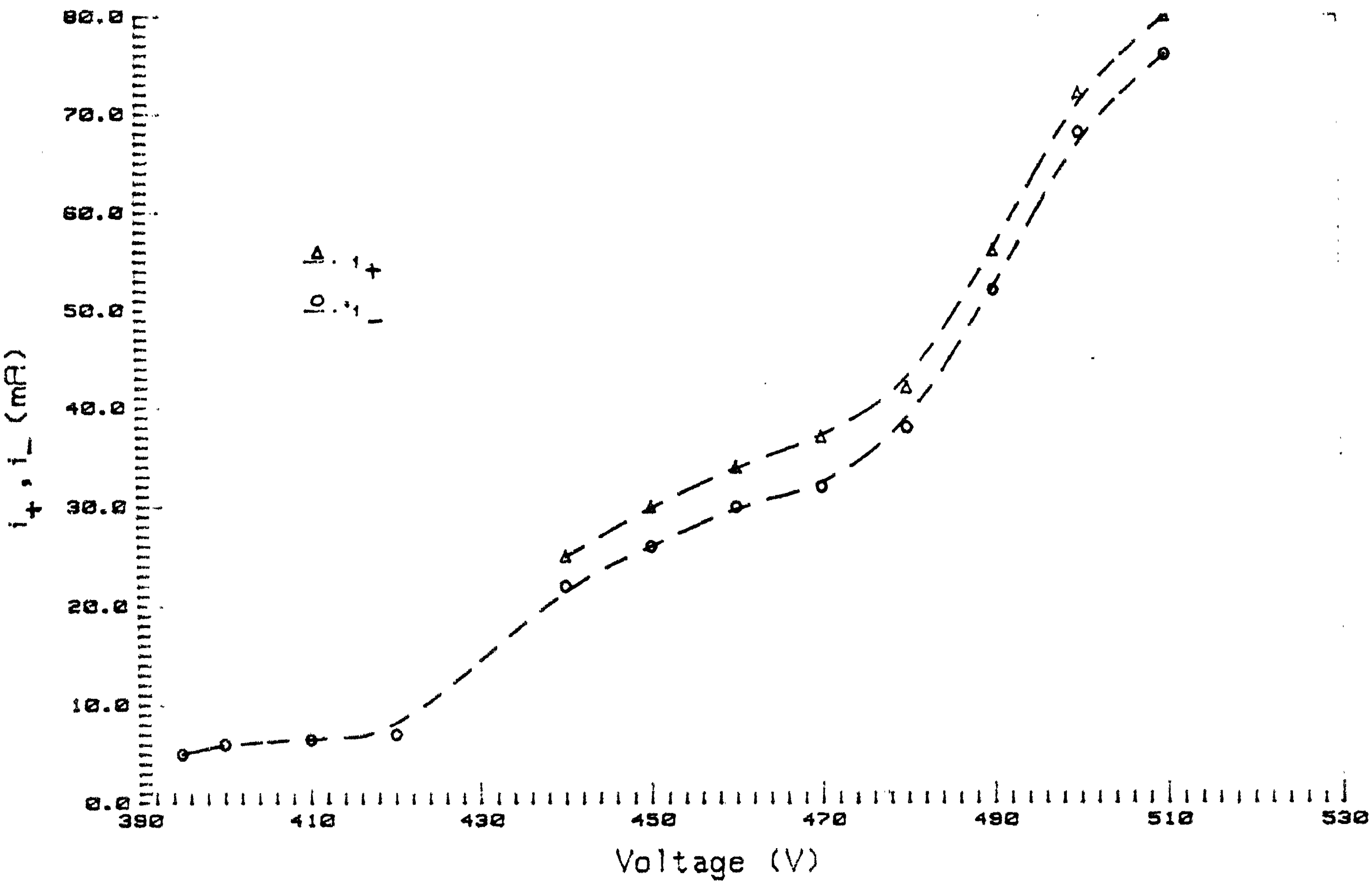

Fig. 4.9: Graphical representation of Table 4.5.

4.2.2 Small Sphere - Large Sphere Gap

37 mm gap

$V_i = 410$ V

$V_b = 510$ V

Table 4.6: Peak values of conduction current under glow discharge conditions for small sphere – large sphere electrodes at constant gap distance of 37 mm.

V (Volts)	i^- (mA)	i^+ (mA)
410	–	10
420	16	10
430	20	16
440	24	22
450	30	27
460	35	34
470	44	44
480	58	58
490	66	66
500	80	80

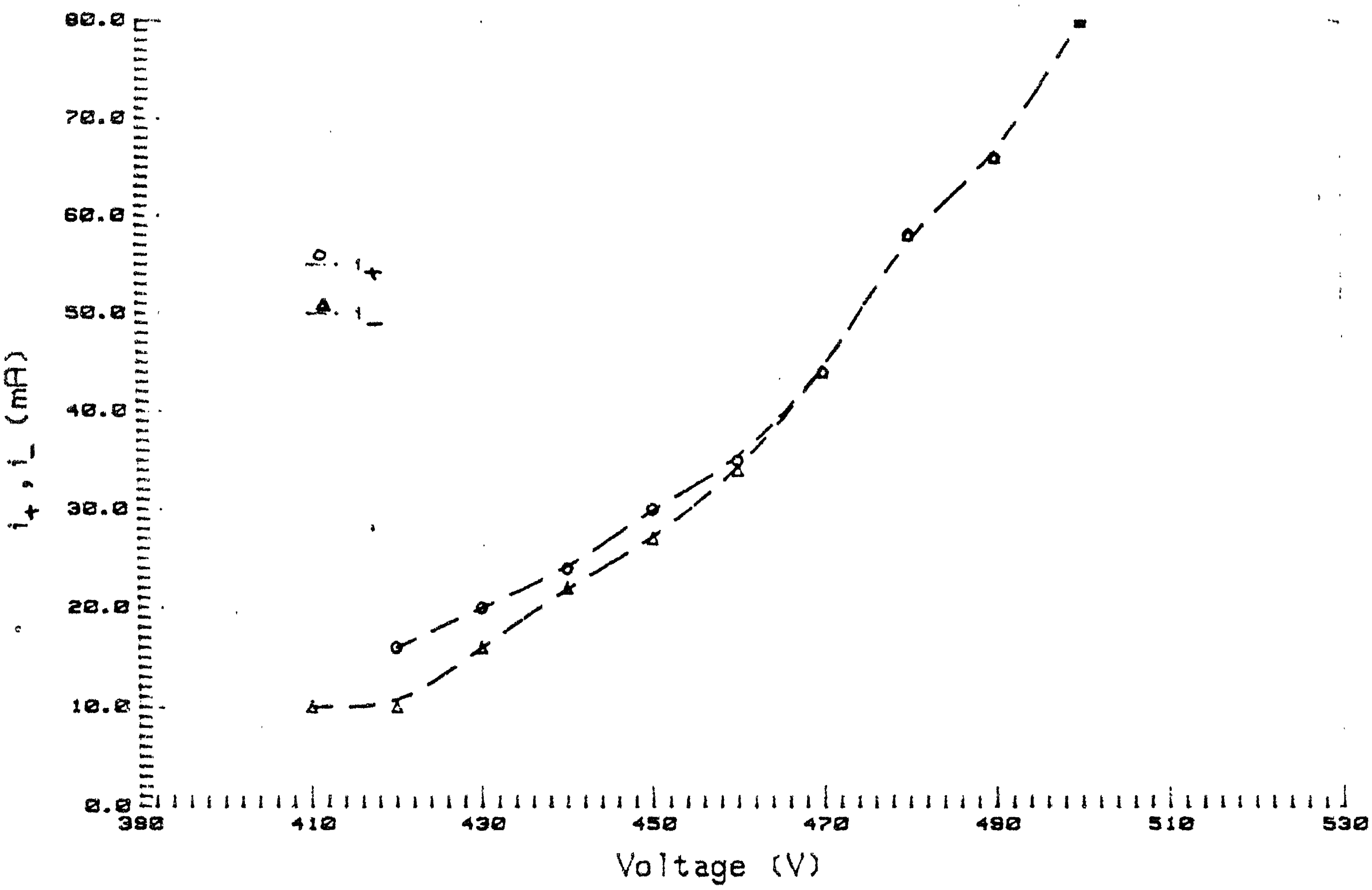

Fig. 4.10: Graphical representation of Table 4.6.

CHAPTER 5

ANALYSIS OF RESULTS AND CONCLUSIONS

5.1 BREAKDOWN STRENGTH

The electric strength of air is found to reduce gradually when the pressure is decreased from atmospheric to a value of 1 Torr.

1. For the 3 cm point sphere gap the mean breakdown strength of air decreased from 9.8 $k\hat{V}/cm$ at 684 Torr to 2.8 $k\hat{V}/cm$ at 76 Torr (Fig. 4.2).
2. For the 5 cm point sphere gap, the mean breakdown strength deceased from 8.6 $k\hat{V}/cm$ at 684 Torr to 3.3 $k\hat{V}/cm$ at 76 Torr (Fig. 4.1).
3. For the small sphere - large sphere gap with a gap distance of 3.7 cm the breakdown strength decreased from 14 $k\hat{V}/cm$ at 684 Torr to 4 $k\hat{V}/cm$ at 76 Torr (Fig. 4.5).

For all the above electrode configurations and gap length settings, an extremely low value of breakdown strength was measured at the pressure of 1 Torr when a bright glow discharge were observed all over the electrodes. The breakdown voltages for these conditions were between 510 - 525 V. Besides, high conduction currents could also be measured under these conditions as described in the following.

The above values of breakdown strengths refer to peak voltage considering a sinusoidal waveform of the applied voltage.

5.2 PD INCEPTION VOLTAGE

PD inception voltage refers to the applied voltage on the HV electrode at which partial breakdown of the gas (corona) incept under the given conditions. This voltage when measured with decreasing pressure did change in a peculiar manner. A minimum of PD inception voltage was measured for a given electrode setting at a particular pressure.

1. For the 5 cm point-sphere gap, the PD inception voltage was minimum at a pressure of 482 ~~532~~ Torr. At this pressure, the inception voltage was 12.5 kV (Fig. 4.3).
2. For the 3 cm point-sphere gap, the PD inception voltage was minimum at a pressure of 532 Torr. At this pressure, the inception voltage was 15 kV (Fig. 4.3).
3. For the point-sphere gap, the variation of inception voltage with pressure was similar for both the gap distances (3 cm and 5 cm) observed. This can be observed in Fig. 4.3.

5.3 OBSERVATION OF FARADAY GLOW AND THE MEASUREMENT OF CONDUCTION CURRENTS

1. On lowering the pressure in the vessel to the level of 1 Torr a bright glow discharge was observed all over both the electrodes on applying a voltage of 400 V and above. The brightness of this discharge was not uniform all over the electrodes. It was observed to be more at sharp points or edges. One can conclude from this that the glow discharge was brighter in the regions of higher electric fields.

2. At a certain range of pressures, the electrons that strike neutral atoms or molecules have energy that is not sufficient to

ionise the atom. However, the atoms may get excited to higher energy states on collision with these electrons (i.e. the outer most electrons of the atoms go to higher energy states of the same atom). The higher energy states are unstable and when the excited electrons of these atoms fall back to their original states, the difference in energy is released as photons, causing a glow discharge.

3. The glow discharge in the space between the electrodes was observed with clear bright and dark rings alternatively.

4. The conduction current measured according to the circuit described could be measured only under the glow discharge conditions. For all the electrode configurations and gap settings the conduction currents were first observed at the negative peak of the applied voltage. On increasing the applied voltage conduction currents were observed on both the half cycles.

5. The breakdown voltage of the gap was independent of gap distance for the point-sphere electrodes. The glow inception voltage however, was dependant upon the gap distance and increased with increasing gap distance.

6. For the small sphere - large sphere gap, the negative and positive peaks of the conduction currents were equal at voltages close to breakdown. Whereas for the point-sphere electrodes the positive peak was measured to be greater than the negative peak (Fig. 4.8 - 4.10).

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APPENDIX A

PHYSICAL PROPERTIES OF LOW VACUUM

The molecular density of air at atmospheric pressure is 2.5 x 10^{19} molecules/cm^3 and vacuum is defined as space where the molelcular density is less than this value. Conventionally, low vacuum refers to pressure range between any value less than 760 Torr and 10^{-3} Torr.

A tabulation of the physical properties of low vacuum as given by Roth /4/ is given below.

Table A: Parameter values describing low vacuum.

P Torr	n molec/cm^3	ϕ molec/cm^2.s	λ cm
760	2.46×10^{19}	2.88×10^{23}	6.7×10^{-6}
1	3.25×10^{16}	3.78×10^{20}	5.1×10^{-3}

P = pressure

n = molecular density

ϕ = molecular incidence rate (the rate at which molecules strike a surface)

λ = mean free path (average distance that a molecule of air travels between two successive collisions with other air molecules).

APPENDIX B

COMPOSITION OF LOW VACUUM

In the low vacuum range the composition of air resembles that of air at atmospheric pressure. In higher vacuum the composition changes towards one in which water vapour, hydrogen & carbon monoxide dominate. /4/

Table B: Composition of air at 1 atmosphere.

Component	% by volume	Partial (Torr).
N_2	78.08	5.95×10^2
O_2	20.95	1.59×10^2
Ar	0.93	7.05
CO_2	0.033	2.5×10^{-1}
Ne	1.8×10^{-3}	1.4×10^{-2}
He	5.24×10^{-4}	4×10^{-3}
Kr	1.1×10^{-4}	8.4×10^{-4}
H_2	5.0×10^{-5}	3.8×10^{-4}
Xe	8.7×10^{-6}	6.6×10^{-5}
H_2O	1.57	1.19×10^1
CH_4	2×10^{-4}	1.5×10^{-3}
O_3	7×10^{-6}	5.3×10^{-5}
N_2O	5×10^{-5}	3.8×10^{-4}
CO	–	–